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Study of climactic changes in the upper Quaternary from ice cores

A review of recent research

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Abstract

This dissertation begins with an description of the mechanisms of climate change, from the interactions between the various mechanism through the astronomical theories and the explanation of feedbacks. The next chapter tells the history of ice coring from sorges snow pit research in the 1930's to the latest Vostok and EPICA Dome C antarctic cores and the NGRIP arctic core. Next the methods of ice coring are explained starting from the drill site selection through the drilling and processing of the ice cores themselves. Next the climates of the middle Pleistocene are describes and the Eemian warm interglacial period, and the climate of the upper Pleistocene with Bølling-Allerød interstadials warm periods and the younger dryas stadial cold period. Last the climate of the Holocene is described in detail including worldwide climactic conditions and the high variability and Rapid Climactic Change events that dominates the Holocene.

Introduction

In this dissertation I will give an general overview of the climactic conditions on earth as described in the scientific research of ice cores, encompassing the last 800,000 years. An background to understanding the causes for these climactic changes is also provided in the form of an overview of the mechanism of climate change, and a brief review of the history of arctic and antarctic ice coring and the methods used for analyzing these cores. It is important to provide this overview of past climactic conditions as a reference for future research into climactic changes, particularly Rapid Climactic Changes, as we are in the middle of one such Rapid Climactic Change now, in order to understand the reasons for the current climactic change and to be able to predict it's outcome. If future researches will have an overview of past climactic changes on earth they will be able to put the current changes in the correct perspective and deduct meaningful conclusions about the present and future climate.

The mechanisms of climate change

There are several theories that try to explain the mechanisms and reasons for climactic changes on every scale. But many of these theories cannot explain on their own all the climactic changes that happening and happened on earth. In order to explain fully all the climactic changes a combination of factors and theories need to be taken into account, some of them probably are yet to be discovered.

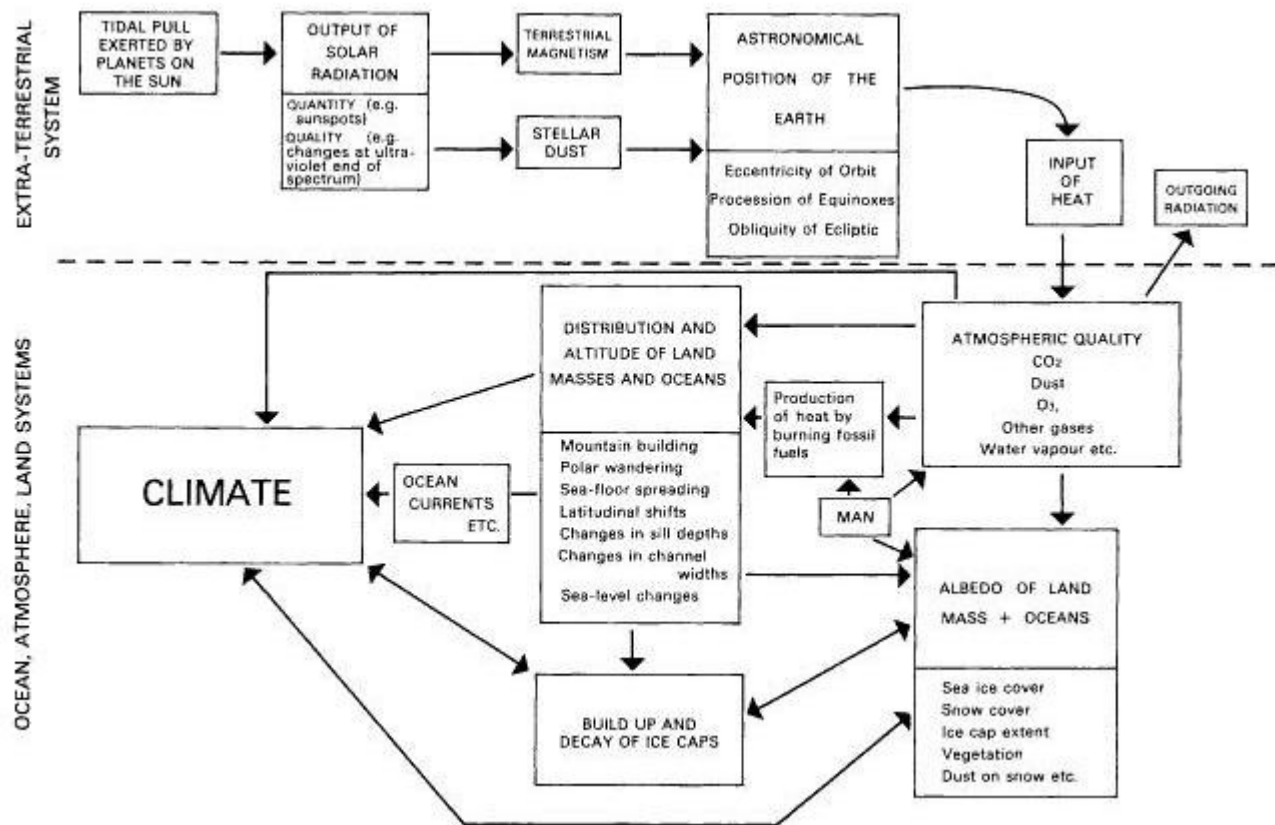


Figure 1: A chart showing some of the factors that affect the earth's climate and their relationships (Goudie, 1992)

This chapter will review some of the major theories that try to explain climactic changes.

Theories about the causes of global climate change

Starting from outer space the first theory is trying to explain the effect of changes in output of solar radiation on the climate. It had been recognized that the sun's radiation changes over time by quantity

and quality. Many researchers with eleven had established cycles of solar activity for the short term and twenty-two year cycles being the ones particularly noticed, and an eighty to ninety years cycle being theorized. During the last 300 years or so (the period in history where reliable instrument record exists) it had been found by some researchers that there is a strong correlation between some periodic meteorological phenomenon and sunspot activity, while other periodic meteorological phenomenon has no statistically significant correlation with sunspot activity. For example, Strongfellow plotted in 1974 the five-year moving mean of lightning activity for 1930-1973 and found a 0.8 correlation with sunspot activity, and an eleven-year cycle. Although the role of changes in solar activity has frequently had been attacked, especially with regard to cycles, some striking correlation have been found between solar activity and certain major characteristics of the general atmospheric circulation. In addition, the observation of sunspots in historical times can give a measure of climate conditions on earth. For example between 1640 AD and 1710 AD there was an almost complete absence of sunspots, the significance of this solar activity minimum (sometimes called the Maunder minimum) is that it occurred during some of the more extreme years of the little ice age. (Goudie, 1992)

The second astronomical theory concerning climate change is the Croll-Milankovich theory. It concerns with the configuration of earth's orbit and its orientation. There are three main factors that been identified as being important for explanation of the effect of changes in orbital configuration and planetary orientation on climate change. It is important to notice that all three factors occur in a cyclic manner. The first one is changes in the eccentricity in earth's orbit (occurring in a cycle of 96000 years). The second one is the precession of the equinoxes (with periodicity of 21000 years). In addition, the third one is changes in the obliquity of the ecliptic (with a cycle of 40000 years). (Goudie, 1992)

An non astronomical mechanism of climate change are Feedbacks. An important one is the ocean conveyor belt in which salt and cold water become denser and sinks to the bottom of the ocean, in the north Atlantic, and then flows to less dense areas where it rises heats up, in the tropic, the hot and relatively desalinated water flow north and heat up the high latitudes. (Mayewski, White, 2002) If a considerable amount of fresh water, for example from melting ice, flows into the north Atlantic the oceanic conveyor belt stops and the earth experiences an drop of temperature due to increased ice mass and albedo which causes an reduction in absorbed solar energy. Other factors that can contribute to climate change through feedbacks are the amount of solar radiation that reaches the earth, the amount of CO₂ and methane in the atmosphere and also amount of volcanic dust and gases. (Mayewski et al., 2004)

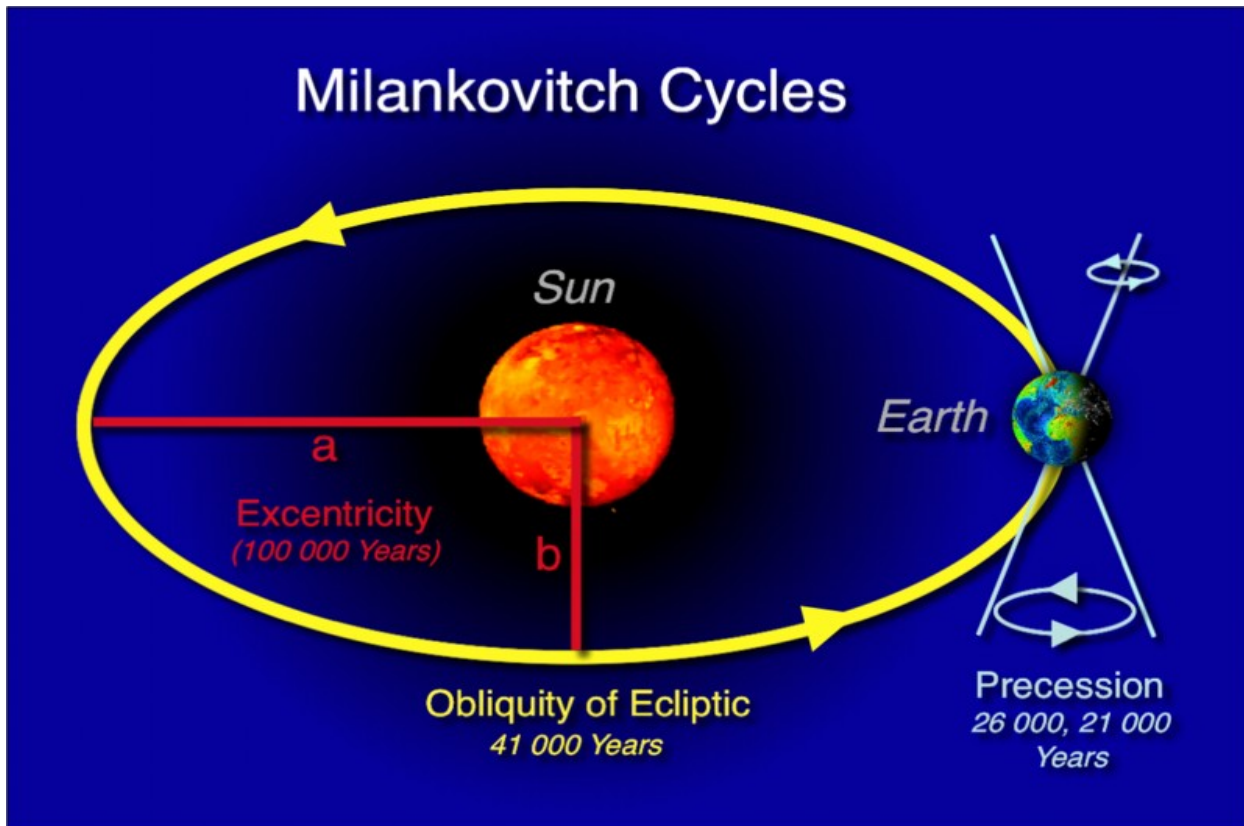


Figure 2: Milanković-Cycles (by Hannes Grobe, Alfred Wegener Institute for Polar and Marine Research)

The third theory tries to explain climatological conditions as a variation of the earth's magnetism. The work that is being done into this theory shows a definite correlation between the strength of the magnetic field and temperature, but this effect seems to be a local effect. (Goudie, 1992)

The fourth theory tries to explain climate change by connecting it to atmospheric transparency. In particular, great importance has been attached to the role of volcanic dust emissions. The presence of elevated dust levels in the atmosphere could increase the backscattering of incoming solar radiation, further more dust and volcanic dust in particular might reduce sunshine totals by acting as a condensation nuclei and promoting cloudiness. This theory also called Global Dimming. (Goudie, 1992)

History of ice coring

The study of the deep interior of ice sheets began to evolve in Greenland and Spitzbergen in the early 1930's. Ernst Sorge conducted the first systematic and quantitative research of the near-surface firn strata (15-meter deep pit) during the Alfred Wegner expedition to central Greenland. Sorge hand dug a pit adjacent to his snow dug living quarters. After seven months of meticulous examination of the structural features and measurement of the physical properties of the pit profile, Sorge determined the characteristics of the individual limits of annual snow accumulation. Sorges data was later transformed into a mathematical expression by Bader, which used it in his own study of annual strata in 1953. Bader performed his study in Northwest Greenland by excavating a 37-meter pit, and later extending it to 47-meters by using a hang auger. (Chaser, Langway, 2008)

Around 1950, almost simultaneously, three international research teams, in three different remote areas and using three different ice-coring rigs were mounted. One was during 1949-1952 by members of Norwegian-British-Swedish Antarctic expedition (NBSAE), they cored to nearly 100-meters on the polar ice shelf along the Queen Maud Land Coast, Antarctica. The second was during 1949-1950 by members of the Juneau Ice Field Research Project (JIRP), they cored to about 100-meters into the temperate Taku glacier in Alaska. The third team was during 1950-1951 by members of Expéditions Polaires Françaises (EPF), they bored two holes 126 and 150 meters on the central Greenland inland ice at Camp VI and station Central. All three efforts reported only marginal success in terms of anticipated depth reached and quality of ice retrieved. The poor physical condition of the ice and large gaps in the core precluded stratigraphic analysis. (Chaser, Langway, 2008)

Between 1952 and 1955, Carl Benson with Richard Ragle and others made a systematic study of the distribution of the regional, near surface snow accumulation over nearly the entire surface of the Iceland ice sheet. This effort resulted in a detailed regional mass-balanced study over a large portion of the inland Greenland ice sheet. In some pits (about 4-meters deep), widely spaced samples of snow and firn were collected for oxygen isotope analysis by Samuel Epstein in California institute of technology. In spite of non-continuous and wide spaced samples, the oxygen analysis yielded data that suggested a relationship between seasonal snowfalls. In the late 1950's oxygen analysis was used as a standard in the 411-meter deep SIPRE site-2 ice core to reliably determine annual accumulation cycles. (Chaser, Langway, 2008)

The late 1950's were a time of renewed interest in international polar latitude research, culminating in the International Geophysical Year (IGY) in 1957-1958. The IGY Antarctic glaciology research

program involved the effort of 12 nations, with 48 stations on the continent. The arctic glaciology research program involved 14 nations, with 302 stations north of the 60's parallel. (Chaser, Langway, 2008)

The snow ice and permafrost research establishment (SIPRE) pre IGY pilot drilling trials were successfully conducted at site-2, North West Greenland in 1956 reaching 305-meters and in 1957 reaching 411-meters. Due to the higher quality continuity and the minimal amount of gaps in the 1957 core (as opposed to the 1956 core) it was selected for detailed laboratory investigation. A time study of stress relaxation of core specimens as a function of depth and increasing hydrostatic load pressure that existed at their depth of recovery were conducted in a laboratory on the ice shelf and the repeated 12 and 18 months later. Further studies were made in the field these include embedded particle concentrations and thin-section crystal analysis at selected core depths. Later a cooperative study was conducted with Samuel Epstein from the California institute of technology and Russell Werby laboratory, the first measured stable oxygen isotope ratios and the second measured ionic concentration levels on horizontal adjacent core samples. This complete investigation marks the first, state of the art, integrated scientific investigation of a deep ice core. (Chaser, Langway, 2008)

The Greenland drilling were closely followed by successful IGY drilling's in Antarctica, at Byrd station in 1957-1958 reaching 307 meters, and Little America V, on the Ross ice shelf in 1958-1959 reaching 264 meters into sea water. (Chaser, Langway, 2008)

The overall success of IGY's core drilling's and ice core analysis in Greenland and Antarctica has sparked an interest in polar and sub-polar research. The SIPRE team had already seen the need for a more powerful coring rig to reach bedrock depths. The first leg of the Cold Regions Research and Engineering Laboratory (CRREL) post IGY bedrock core drilling project originated at camp Tuto on the edge of the ice sheet in the summers of 1959-1960. The operation was moved in 1960 to camp century where three cores were retrieved using a new cable suspended thermal coring rig. The first in 1961 reached 186 meters before the drill got stuck and the bore hole abandoned, the second one in 1962 reached 238 meters where the heating head was lost and the hole had to be abandoned, a third hole was started in 1963 which reached 264 meters. The 1963 hole was re-entered in 1964 and extended to 535 meters. In 1965 due to unsatisfactory performance of a thermal drill in a fluid filled hole, the rig was replaced with an electro mechanical drill. The new drill was inserted into the 535-meter borehole in and reached the base of the ice sheet in July 1966 at 1387 meters. The same drill and drilling team went to Byrd station, Antarctica in the fall of 1966 for the second leg of post IGY project.

They successfully reached bottom ice at 2164 meters in January 1968. (Chaser, Langway, 2008)

In 1970, a group of scientist and engineers from the United States, Denmark and Switzerland began to plan a new ice-coring program. The Greenland ice sheet program (GISP) was directed toward further investigation of, the fuller scope, extent, and reproducibility of the new climactic and other environmental records that were discovered at camp century and Byrd station cores. The GISP operation required an 11-year field period. The first seven years were occupied by various preparatory and auxiliary science studies in both field and laboratories to determine the optimal deep drilling site locations. Originally GISP was planned to have three bedrock core drilling's but due to financial constrains the program was scaled back to one location, the logistically convenient Dye-3. The Dye-3 deep bedrock drilling started in 1979 and reached bedrock in august of 1981 at 2037 meters. (Chaser, Langway, 2008)

As concern over climate change and global warming built, many people raised the call for new Greenland ice cores in the right places. The best way to achieve this was to collect two deep cores close to each other and compare them. This need produced the Greenland ice core project (GRIP) and Greenland ice sheet program two (GISP2) projects. The first was mostly a European consortium and drilled through the summit of the ice cap between 1989 and 1992 reaching a depth of 3028 meters. In addition, the second one was a mainly US effort and drilled through the ice about 30 kilometers west of GRIP between 1989 and 1993 and reaching a depth of 3053 meters. (Alley, 2000)

In later years, more deep cores were retrieved in Dome F in Antarctica where between 1993 and 1995 a core was bored to a depth of 2503 meters (Kawamura et al., 2007) and the Vostok ice core drilled between 1993 and 1996 and reached a depth of 3623 meters. It is notable to mention the European Project For Ice Coring in Antarctica and North GRIP as two projects that provided cores in the last ten years, just to mention a few.

Methods

The process of retrieving an ice core begins by selecting a drill site. Drill sites are selected by preliminary research in the intended drill area. The researchers arrive at a proposed drill site and dig a snow pit 2 to 6 meters deep by hand in order to avoid local contamination from fossil-fuel burning engines. A retrieval team preserves and sends samples of the ice pit back to the laboratory where it is determined if whether well-preserved signals clearly identify the different climate conditions in the years being studies. The team also considers how spatially representative the site is, how well it reveals climate history over a specific region or the entire globe. A radar survey of potential sites is also conducted to determine the relief of the bedrock underneath, the flatter the bedrock the less deformation in the ice exists. (Mayewski, White, 2002)

Eventually when the drill site is located, the research and drilling team returns with drills of various sizes and types, depending on the requirements of the project. The drills range from small solar powered drills for shallow cores through drills powered by small gas engines for retrieving around 100 meter cores and to big drills powered by 2 to 5 kilowatt generators and able to drill to a depth of over 3000 meters. (Mayewski, White, 2002)

Typical drills produce a core 101 millimeter in diameter. With each run, a 4 to 6 meter ice core was retrieved. The drill itself is lowered into the borehole on a long (in case of bedrock drills over 3500 meters) cable. Because ice deforms easily under pressure, the hole formed by drilling would collapse on itself if there were nothing to in the hole to supply back pressure. Therefore, a fluid is poured into the borehole to provide back pressure. (Mayewski, White, 2002)

After the core is retrieved, the science team cuts the core into samples and performs an on-site analysis to allow for preliminary core dating a first overview of the climates record. In order for the core to produce valuable environmental data, it needs to meet three key criteria:

1. *The record must be well dated over a long period of time.* This is achieved by counting the annual layers from the top of the core to the bottom of the core and so, figuring out how many years before the present the layers represent. The first step in this visual identification process is to shine a light through the core. It is possible to tell the difference in layers by either changes in the dust contents or a season-to-season alterations in the ice density. Summer layers are less dense than winter layers because wind compact the winter layers. Moreover, during the winter-spring period, the strong winds blowing across Asia and North America carry dust into Greenland. A further method for identifying annual layers is

electrical conductivity, a method adapted by Kendrick Taylor from the work of Claus Hammer, a special device “runs” across the surface of the ice core and measures electric conductivity levels to the millimeter scale. The difference in electrical conductivity in ice is the result of (and indication for) the presence of strong acids. Yet another way to date and calibrate an ice core is by analyzing the oxygen in gas bubbles trapped in the ice. Oxygen is important for climate research because as a gas it mixes globally and biological activity embeds a special signature in the oxygen, this signal changes over time, and two ice cores of equal age should each have the same biologically introduced oxygen signal.

2. *The record must be of a high resolution and continuous.* This is achieved by sampling the record at as high intervals as possible. For example, the GISP2 project sampled the ice every 2 years over the past 10000 years, at least every 15 years for the period from 10000 to 45000 years ago, and at least 50 years from 45000 to 110000 years ago.

3. *The record must include a sufficient number of properties.* The ice cores needs to be sampled for as many indicators as possible; GISP2 sampled and measured almost fifty different measurements for any specific layer. (Mayewski, White, 2002)

since stable water isotope measurements are particularly important they merit an in depth explanation. All the atoms of the same element have the same number of protons in their nuclei, but the number of neutrons may differ, yielding a different mass and creating an isotope. Two important isotopes in ice core research are oxygen and hydrogen. The isotopes of oxygen and hydrogen are especially useful in providing information on the history of temperature. The most common oxygen isotope is ^{16}O with 16 protons, and the next most common after it is ^{18}O with two additional protons. Water with the formula H_2^{18}O behaves chemically the same as water with ^{16}O but because it is heavier it condenses more readily. The ratios of ^{18}O to ^{16}O depends primarily on the temperature at the time the water condensed. By measuring the ratio of the two isotopes it is possible to calculate the temperature at the time the snow fell, because the heavier isotope is precipitated out as the temperature drops and/or with the distance of transport leaving more of the lighter isotope. (Mayewski, White, 2002)

Another important environmental data proxy that is measured in ice cores is the chemical that compose the ice. Almost all of the chemical composition of ice are the following substances: chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{++}), calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+) and methanesulfonate (MS). Changes in the concentration of chemical species in ice are related to changes in source emissions and/or changes in the transport path of the chemical to the ice core site. Snow and ice from Greenland may contain dust from Asia or north America, it may

contain volcanic sulfate from Indonesia or Alaska. Sodium and chloride may be from sea salt droplets from the mid Atlantic, ammonium from terrestrial biota. These chemicals can tell us about what conditions existed in the source locations of the chemicals or in the location where these chemicals pass en route.

Climate of the middle Pleistocene

One of the paradoxes of Quaternary climate is the dominance of 100 kyr BP periodicity in the past few climatic cycles, even though the amplitude of insolation changes at this period is rather small. On the basis of mainly ice volume records, two major transitions have been identified. The mid-Pleistocene transition (MPT) is characterized by an increase in mean global ice volume and a change in the dominant periodicity from 41 kyr BP to 100 kyr BP it is usually timed at 900 kyr BP. A second distinct climate change, the mid-Brunhes event (MBE), roughly corresponds to the transition between stage 12 and stage 11 (these are isotopic stages used in dating deep sea cores) it is dated to about 430 kyr BP. The MBE is characterized by a further increase of ice-volume variations with, from then to present day, four large-amplitude 100 kyr dominated glacial interglacial cycles. The period between MPT and MBE has a less defined pattern. (EPICA community members, 2004; Rial, 2003)

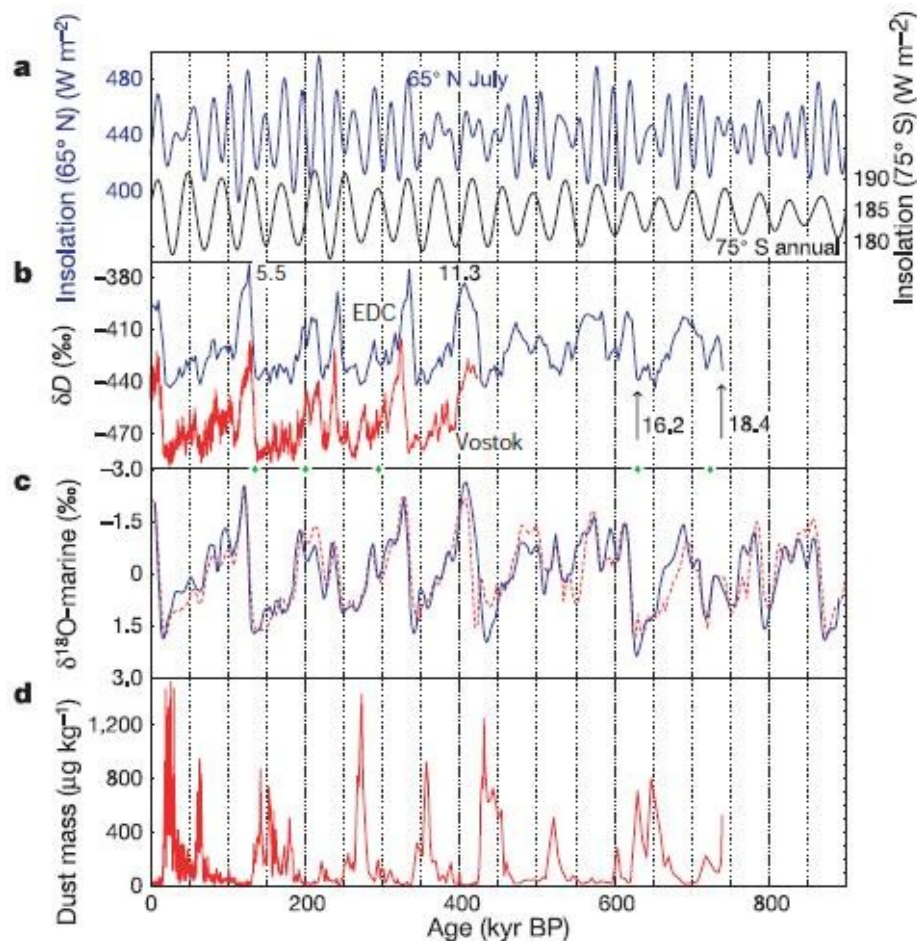


Figure 3: EPICA Dome C records (EPICA community members, 2004)

There is very little research done into this period of time using ice cores. Most of the research uses deep

sea cores; this is because only one ice core that dates to this time exists (EPICA dome C).

Climate of the upper Pleistocene

The upper Pleistocene is a geological period dating from 126 kyr BP to 11.7 kyr BP, in the ICS time scale this period is referred as the Tarantian stage. The upper Pleistocene consists of a number of climactic periods and a single glacial-interglacial cycle.

Eemian climactic period and beyond

The NGRIP records show that the Eemian period (130 kyr BP to 114 kyr BP) maximum isotopic value is -32‰, which is 3‰ higher than the present day value (of -35‰). These changes are attributed solely to higher temperatures due to the sampling of the NGRIP ice of the warmest part of Eemian climate. This difference of isotopic values indicates an at least 5°C warmer temperature in the Eemian than the present. The Eemian isotopic values recovered from NGRIP paint a picture of an Eemian ice sheet with northern and central ice thickness similar to the present, while the south Greenland ice thickness is substantially reduced. (EPICA community members, 2004)

The EPICA Dome C isotope record (ΔT_{db} and $\Delta T_{\delta^{18}\text{O}}$) exhibit a 1.5°C decrease from 45 to 41 kyr BP and then an rise of 2°C to a broad maximum that extends to a 28 kyr BP, with values about 1°C above Last Glacial Maximum level. The EPICA Dome C core has shown slow temperature fluctuations that reflect changes in the annual mean insolation caused by changes in the earth's tilt. The minimum obliquity, at about 29 kyr BP, corresponds to warmer low latitudes and colder high latitudes. The EPICA core shows a strong cooling at about 41 kyr BP followed by an increase in temperatures significantly above the glacial maximum level. By comparing Antarctic and arctic ice core record it is noticed that the maximum temperature values are reached much later in the southern hemisphere than the northern hemisphere. The latitudinal temperature gradient exhibits gradient a marked decrease during the A1 event (corresponding to D/O event 8 at 38 kyr BP), followed by an progressive increase until about 27 kyr BP, when the temperature reaches a maximum value, and high values until 18 kyr BP. In addition to the progressive increase, attributed to obliquity changes which modulate the meridional annual mean insolation gradient, two large events are observed: first, the large decrease during A1 at 38 kyr BP; second, a large increase from 28 to 24 kyr BP. This second event corresponds to a cold period in Antarctica and intermediate temperatures in the rest of the southern hemisphere. (Stenni et al., 2003)

A study of the $\delta^{18}\text{O}$ and Potassium records of the Greenland GISP2 ice core suggested a strengthening

of the Siberian high during stadials and weakening during interstadials. It also suggests the recurrence of DO event in multiples of 1470. (Schulz et.al., 2004)

Bølling-Allerød interstadial and the younger Dryas stadial

According to $\delta^{18}\text{O}$ analysis of the NGRIP ice core the warming of the Bølling interstadial, dated at 14.7 kyr BP, took about 3 years and represented a warming of more than 10°K . According to the same records the cooling at the beginning of the younger dryas, Dated at 12.9 kyr BP, lasted more than two centuries. Annual layer thickness has increased by 40% during the Bølling-Allerød warming over 3 and 40 years respectively and decreased by 33% during the younger dryas over a period of 152 years. (Steffensen et al., 2008)

Insoluble dust and Ca^{2+} concentrations reflect source strength and transport conditions from the source, which are the low-altitude Asian deserts. These records indicate that during the Bølling-Allerød warming events the dust and Ca^{2+} concentrations decreased by a factor of 5 to 7 within a few decades, in contrast during the younger dryas cooling event dust and Ca^{2+} concentration increased by a factor of 5 over a century. (Steffensen et al., 2008)

During the end of the younger dryas snow accumulation rate had doubled from approximately 0.07 ± 0.01 to 0.14 ± 0.02 m ice/yr, in one to a few years. An additional increase of 50-100% brought the snow accumulation rate to the modern 0.24 m ice/yr. the end of the younger dryas also brought a drop in dust, Ca^{2+} and sea salt concentrations, sea salt dropped by three fold and sub one micron dust concentrations dropped by four fold and a seven fold drop in 3-10 micron dust and Ca^{2+} . These changes are attributed to several changes that happened during the younger dryas, stronger winds and drier atmosphere which resulted in reduced precipitation produced higher loadings of dust and sea salt with shorter transport times and less fallout and scavenging by precipitation en route. All of these produced high concentrations of dust, Ca^{2+} and sea salt during the younger dryas and pronounced the drop in these aerosols. (Alley, 2000)

The estimated temperature of the younger dryas is about 15°K lower than today, with the warming to today's temperature occurring in an abrupt $5\text{-}10^\circ$ step during a few decades or less and the rest during the millennium following the younger dryas. The atmospheric composition during the younger dryas did not produce any significant anomalies in CO_2 , but a noticeable reduction of methane concentration during the younger dryas. Methane concentration was 700 ppbv before the younger dryas and almost 750 ppbv after the younger dryas, but during the younger dryas methane concentration fell to 475 ppbv. (Alley, 2000)

The high resolution study of the NGRIP core demonstrated that the last two warming's followed the

same general pattern. During Greenland cold phases, the thermohaline circulation (THC) was reduced, northern sea ice extended far south, and the inter-tropical convergence zone (ITCZ) was shifted southward, resulting in dry conditions in the low latitudes regions (the dust source regions for Greenland). Mean while, southern high latitudes and tropical oceans accumulated heat and underwent gradual warming as reflected in the bipolar seesaw pattern, because of a reduction in the north Atlantic overturning circulation. This southern hemisphere/tropical warming induced first a northward shift of the ITCZ and. And second, when a threshold was reached, an abrupt intensification of the Pacific monsoon. The wetter conditions at the Asian dust source areas then caused decreased uplift and increased washout of atmospheric dust and Ca^{2+} concentrations. This reorganization of the tropical atmospheric circulation was followed by a complete reorganization of the mid to high latitude atmospheric circulation almost from one year to the next. Both the Bølling-Allerød warming events and the 11.7 kyr BP warming event that marks the beginning of the Holocene are characterized by the same sequence of event, described above, Even though these warmings occurred during different stages of deglaciation. The Bølling-Allerød warming events followed Heinrich event H1 (oldest dryas) at a time when the ice sheets in the north were still extensive, whereas the north was more deglaciated at 11.7 kyr BP, reducing the amount of ice discharge available to change the density of north Atlantic ocean waters and thereby the THC before warming onset. (Steffensen et al., 2008)

It is important to notice that the older dryas (see event 1d in appendix 1) is rarely mentioned due to its extremely short duration making it practically invisible to statistical analysis. The statistical analysis requires a minimum of 150 year climatic state (Steffensen et al., 2008) and because the older dryas is only 200 years long it barely registers in the statistical analysis and models.

Climate in the Holocene

The Holocene is a geological period dating from 11.7 kyr BP to this day. It started with the end of the last glacial period and is marked by a pattern of altering Rapid Climactic Fluctuations (see appendix 2). The records of this period, although reliant to an extent on ice cores, use heavily other sources like tree cores, lake bed cores, pollen research and many other sources. Because of this it is impossible to give a description of Holocene climate using ice cores exclusively.

8.2 kilo year event

The widespread, severe climactic disruption from 9000 to 8000 yr BP is unique among the Holocene Rapid Climate Changes (RCC) intervals because it occurs at a time when large northern hemisphere ice sheets were still present. In the north Atlantic there is a significant short lived cooling called the 8.2 kyr event. It also appears to have generally cool over much of the northern hemisphere throughout this interval, as evidenced by major ice rafting, strengthened atmospheric circulation over the north Atlantic and Siberia, and more frequent polar north-westerly, winter time, outbreaks over the Aegean sea. Mountain glaciers advances occurred in northwestern North America and Scandinavia while glacier retreat occurs in European Alps. At low latitudes, this is a period of widespread aridity that occurs midway through a prolonged humid period that began in the early Holocene. Additionally this time period is followed by a change to more seasonal and torrential rainfall regimes throughout tropical Africa. Summer monsoons over the Arabian Sea and tropical Africa weaken dramatically during this RCC, and trade wind strength and rainfall fluctuates over the Caribbean. Widespread persistent drought occurs in Haiti, the Amazon basin, Pakistan and Africa. And precipitation increases in the Middle East. In the southern hemisphere, polar atmospheric circulation over the east Antarctica is weak, snow accumulation rates in this region decrease, and the direction of temperature change is different in different areas of east and west Antarctica. Grounded ice in the Ross Sea retreats continuing a trend that began earlier in the Holocene. Precipitation generally increases in Chile, most likely due to intensification of southern mid-latitude westerlies. (Mayewski et al., 2004)

Holocene Thermal Maximum

The climactic changes during the Holocene Thermal Maximum (HTM) had been studied in great detail over the western arctic (Kaufman et al., 2004), this climactic period spans two RCCs, and in some

places even three RCCs. On average the HTM began on average 8900 yr BP $\pm$ 2100 yr and ended 5900 yr BP $\pm$ 2600 yr. The HTM is characterized by high spatial heterogeneity. Much of the variability is longitudinal. East Beringia clearly warmed earlier than northern continental Canada; nearly all the sites used in this study where warming took place prior to 11 kyr BP are in Alaska, whereas sites where HTM was significantly later (after 7000 yr BP) are in central interior of Canada surrounding Hudson bay. On average sites in central and eastern Beringia experienced the HTM by 11.3 kyr BP. Some sites mainly in central Beringia do not reveal paleoclimatological evidence of warmer than present conditions anytime during the post glacial interval. In contrast the HTM in northern continental Canada was delayed until 7300 yr BP. The timing of the HTM was generally similar in both marine and terrestrial setting. In the Canadian arctic islands and the Greenland-Iceland regions were reached 8600 yr BP. Regions tended to cool in the order they were warmed. The HTM ended first in central and eastern Beringia around 9100 yr BP, then in Greenland-Iceland around 5400 yr BP, the Canadian arctic islands in 4900 yr BP and finally in continental Canada around 4300 yr BP. The onset of the HTM in the north Atlantic was interrupted by abrupt melt water releases from the decaying Laurentide ice sheet. During the later part of the Holocene geography was similar to present and disruptions by the ice sheet were absent. Temperature increase during the HTM fell within a range of 0.5-3°C in terrestrial setting and more than twice that in marine setting. (kaufman et al., 2004)

From the 8.2 kilo year event to the medieval warm period

The RCCs following the 8.2 kyr event, occurring from 6000 yr BP to 5000 yr BP, from 4200 yr BP to 3800 yr BP, from 3500 yr BP to 2500 yr BP and from 1200 yr BP to 1000 yr BP, were generally characterized by the co-occurrence of high altitude cooling and low altitude aridity. This pattern of cool poles and dry tropics is usually associated with long term climate trends during the Pleistocene. The most extensive RCCs were the 6000 to 5000 yr BP RCC and the 3500 to 2500 yr BP RCC also known as the Roman climate optimum. Less widespread RCCs were the 4200 to 3800 yr BP RCC and the 1200 to 1000 yr BP RCC, also known as the medieval warm period. In the northern hemisphere the 6000-5000 and 3500-2500 yr BP RCC intervals featured north Atlantic ice rafting events, alpine glacier advances and strengthened westerlies over the north Atlantic and Siberia. Cooling over the northeast Mediterranean is related to winter time continental/polar air outbreaks. Westerly winds over central north America strengthen from 6000 to 5000 yr BP, but were weak from 3500 to 2500 yr BP. At lower latitudes the RCC interval from 6000 to 5000 yr BP, marks the end of the early to mid Holocene humid

period in tropical Africa, beginning a long term trend of increasing rainfall variability and aridification, although some areas became wetter. Rainfall decreases in northwest India and southern Tibet. Rainfall in Ecuador and trade winds strength over the Carico basin are relatively stable from 6000-5000 yr BP but highly erratic from 3500 to 2500 yr BP. The latter interval also includes pronounced aridity in east Africa, the Amazon basin, Ecuador and the Caribbean/Bermuda region, but southeast Asia is wet despite a dramatic weakening of winds associated with the summer east Asian monsoon. In the southern hemisphere, glaciers advance in New Zealand, and over Antarctica the atmospheric circulation intensifies and generally lower temperatures that are superimposed on a long term trend of increasing insolation. Colling also effects south Georgia island and sea surface temperatures off southern Africa. Mid latitude Chile is drier during 6000-5000 yr BP, but wetter during 3500-2500 yr BP. (Mayewski et al., 2004)

Evidence of the less extensive RCC events occurring between 4200-3800 yr BP and 1200-1000 yr BP, otherwise known as medieval warm period, appear in fewer records, but the apparent synchrony and wide spatial distribution of those records that do contain such evidence still suggest global scale climactic changes. In the northern hemisphere, winds over the north Atlantic and Siberia are generally weak during the 4200-3800 and 1200-1000 yr BP RCCs, and temperatures fall in western north America and Eurasia. Other climactic disruptions, however, while generally synchronous are highly variable in their distribution. For example glaciers advance in western north America but retreat in Europe during the 4200-3800 yr BP period, and Scandinavian ice seems largely unaffected. Westerlies are exceptionally strong during the 4200-3800 yr BP period, but are nearly unchanged during the 1200-1000 yr BP period. At low latitudes these two RCCs include variable but generally dry conditions in much of tropical Africa and monsoonal Pakistan. in the Cariaco basin, trade winds intensify. In the southern hemisphere little change occurs in polar wind strength. Temperatures fluctuate over Taylor dome and mid latitude Chile during is dry during both of these RCCs. During the 4200-3800 yr BP RCC warming occurs in south Georgia island. New Zealand glaciers advance and eastern south Africa is cool and dry from 1200 to 1000 yr BP. (Mayewski et al., 2004)

The Little ice age

During the little ice age both polar regions were cold and windy, but the low latitude aridity that prevailed during earlier RCC intervals does not generally characterize the tropics during the little ice age. There is also the problem of determining the duration and nature of the later stages of this RCC

interval due to the rarity of high resolution record of this period and potential anthropogenic influences. So this period is only studies through ice cores only from 600 to 150 yr BP, the end of this period is also coincides with the beginning of scientific meteorological records. (Mayewski et al., 2004)

In the northern hemisphere glaciers advance and the westerlies strengthen over the north Atlantic and Siberia, this suggests that climate changes in this RCC interval have the fastest and strongest onset of any in the Holocene, with the possible exception of the 8.2 kyr event. At low latitudes the Cariaco basin becomes more arid, as do Haiti and Florida. Conversely, equatorial east Africa experiences variable but generally humid conditions in a negative association between tropical African humidity and northern temperatures that is unusual for the late quaternary. Increasing river discharge in Pakistan and Ecuador suggests that both Indian monsoon and El-Niño southern oscillation (ENSO) systems are effected. In the southern hemisphere portions of the Antarctic peninsula are warm, but east Antarctica is cold in a similar situation to recent bimodal conditions in temperature on the continent. Wind strengthen over east Antarctica and Amundsen sea. South Georgia island is pretty cool, new Zealand glaciers advance and precipitation in Chile is highly variable but generally high. (Mayewski et al., 2004)

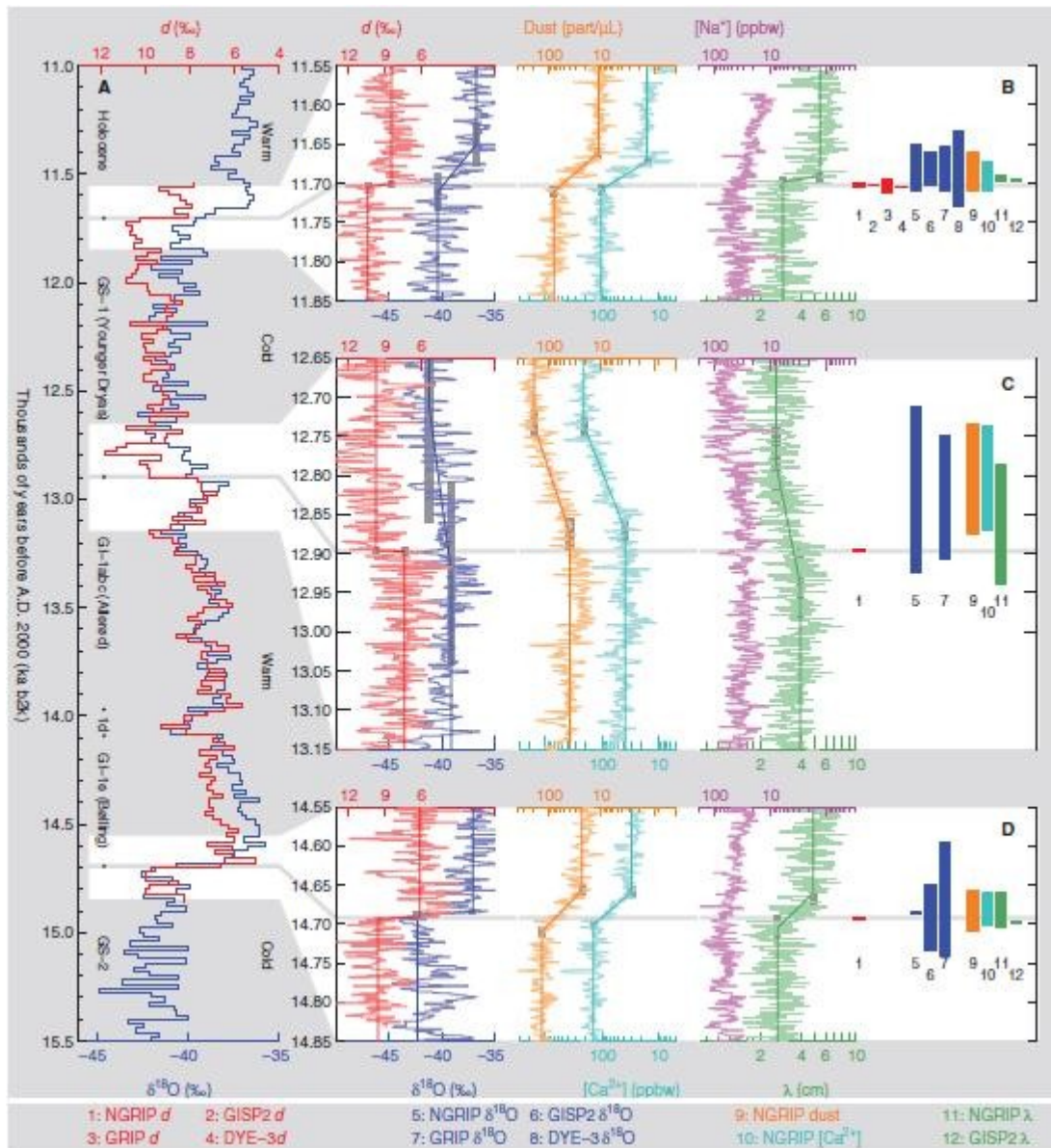
Summery

In this dissertation I provided an general overview of the scientific research in the last ten years into ice cores and the climactic conditions on earth during the past 800,000 years. It is shown that ice cores are mostly used for studying the Holocene, due to it's lack of reach into the far past (there is only one core that dates 800,000 years), but in the ice core record of this earlier history shows an earth with a climate that is being changes slowly by the astronomical forces that described as the Milankovich cycles. These slow changes cause earth's climate to alternate from a glacial cold period to an interglacial warm period. However after the beginning of the Holocene a series of Rapid Climactic Changes occur at a faster rate that what the Milankovich cycles theory can explain. In this case the causes for these changes are variable but mostly has to do with environmental feedbacks, although in some cases of RCC events the cause is less clear due to their lesser magnitude. Finally this dissertation hopefully provides an overview of the major climactic changes and events and helps in the understanding of their cause so we could benefit from past knowledge and have a better understanding of the current climactic changes occurring on earth.

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Appendices



Appendix 1: NGRIP ice core records (Steffensen et al., 2008)

